

## ARCHEAN METAVOLCANIC ROCKS FROM THACKERAY TOWNSHIP, ONTARIO

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### ABSTRACT

The iron-rich Archean submarine metabasalts of Thackeray Township, Ontario, are thought to represent a distinctive magma type: high-iron basalt. High-iron basalt is defined as having >12% by weight FeO (total iron as FeO in the anhydrous analysis). Two well-exposed flows, one of which is a typical high-iron basalt, have been studied in detail. The metamorphism of the region is prehnite-pumpellyite grade yet both flows have original textures and minerals preserved. The chemical composition of the massive parts of the flows appears to be unchanged by the metamorphism, except for H<sub>2</sub>O and CO<sub>2</sub>. Plagioclase was the inferred liquidus phase in both lavas. Pyroxene, hornblende, and Fe/Ti oxide grew during post-eruptive crystallization. The presence of skeletal and frond-like hornblende in the upper part of the iron-rich flow suggests that hornblende may have grown as a quench phase, and was probably metastable. The differentiation of the flows can be modelled by crystal fractionation in which amphibole fractionation plays a key role.

### INTRODUCTION

The metavolcanic and metasedimentary greenstone belts of the Archean shields are of great theoretical and economic importance. Detailed chemical and petrographic descriptions of the basaltic rocks which are common building blocks of the greenstone belts are necessary for the interpretation of the Earth's early history. In this work, we describe a rock type from the Abitibi greenstone belt, "high-iron" basalt. We define high-iron basalts as rocks of generally basaltic composition (45-52% SiO<sub>2</sub>) containing >12% by weight total iron expressed as FeO calculated on an anhydrous basis. This magma type appears to have occurred as subaqueous, hydrous, lava flows which were thick enough to have differentiated during solidification. We have since recognized this rock type in other greenstone belts of the Superior Province of the Canadian Shield.

The rocks of this study are located in northern Thackeray Township, in the central part of the Abitibi Greenstone Belt (the NE corner of the

township is Lat., 48°27'N, Long., 80°01'W). The rocks in this area form part of the Kenogvis Group (D. Pyke, pers. commun. 1974). This area was selected for detailed study after discussion with L. Jensen, who has mapped several townships, including Thackeray, at a scale 1:15840 (1" = ¼ mile) for the Ontario Division of Mines, (Jensen 1969, 1971a, 1971b, 1973). The area has: good outcrop exposure, a subgreenschist grade of regional metamorphism, primary textures and minerals, no structural complications such as penetrative deformations or folding on the scale of an outcrop, and good access by logging roads. Accordingly, this was judged an excellent area for detailed study of one of the important rock types comprising Archean greenstone belts.

The basalts of Thackeray Township lie above, and are probably part of, a 20,000' (6100 m) series of basalts in Garrison Township to the north. Goodwin (1972) reports an average analysis of seven samples from unspecified locations in Garrison Township which were reported to cover the entire section of 6100 m, and this is similar to our results.

### FIELD DESCRIPTION

A general description of the rocks of Thackeray Township is provided by Jensen (1973). The rocks in the northern part of the township are a series of pillowed and massive basalts (Fig. 1a), intercalated with thin chert layers and some thin volcanoclastic units (Fig. 1c). The basalts are typically dark green, fine- to medium-grained, hard, and have a conchoidal fracture. Outcrops are generally rounded and of low relief. The massive, coarser-grained, centers of the flows tend to weather high and commonly display a distinctive texture which, for want of another term, and to draw attention to its significance, we call "reverse-diabasic"\*. In this texture, laths of euhedral hornblende are set in a matrix of plagioclase. Close scrutiny of the weathered surface is necessary to distinguish this texture

\*see footnote on p. 510

from normal diabasic texture (euhedral plagioclase set in a matrix of pyroxene—see Fig. 1b). The fine-grained flow margins are commonly exposed at the edges of outcrops and may easily be missed in routine field work. The high-iron basalts locally exhibit skeletal quench hornblende in the upper parts of the flows, and in pillows.

Minor veins of two ages cut the basalt: an older set containing quartz and epidote, and having diffuse boundaries, and a younger set containing quartz, calcite and minor epidote with sharp boundaries. Meta-domains as described by Smith (1968) and Jolly & Smith (1972) are not developed except as thin selvages along joints and near quartz-bearing faults. Deforma-

tion on the outcrop scale (~30m) has apparently been accomplished by movement on widely spaced, discontinuous fractures now lined with chlorite. Veins of albite are present locally, especially in breccia units (see Fig. 1c).

\*We call this texture "reverse diabasic" because the role of the dark and light minerals are reversed (compared with a diabasic texture). The dark mineral forms euhedral prisms surrounded by the light feldspar. It is important to distinguish these two textures because the one is usually present in intrusions such as dykes, while the other is commonly exhibited by Archean submarine flows. We do not yet know how common this "reverse diabasic" texture is in either Precambrian or Phanerozoic rocks.

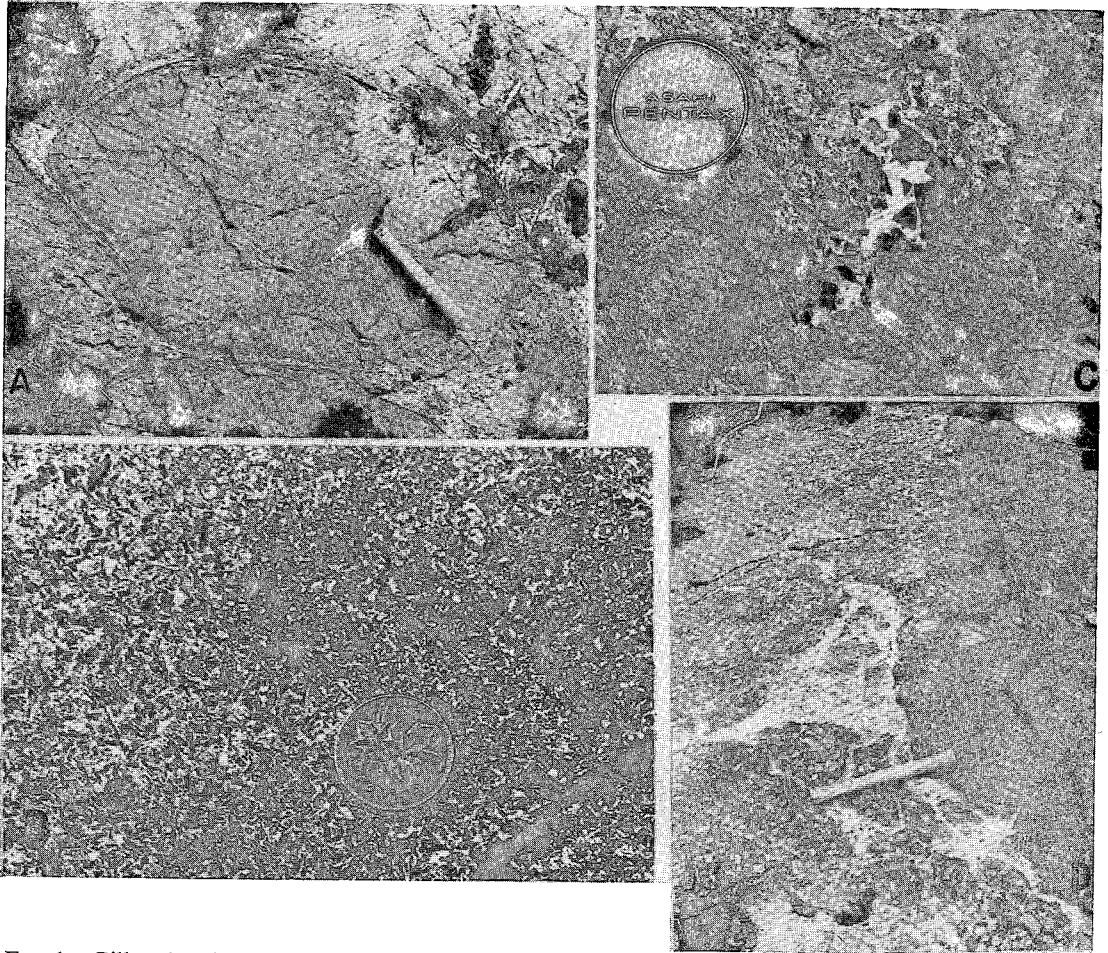


FIG. 1a: Pillow basalt 30 m below Flow 2.

FIG. 1b: Reverse-diabasic textures on an outcrop 10 m below Flow 1.

FIG. 1c: Albite vein cutting volcaniclastic unit immediately below Flow 2.

FIG. 1d: Altered plagioclase phenocrysts interpreted to have floated up in Flow 2. White veins are considered to be the last liquid to crystallize in the flow. The hammer handle points towards the top of the flow.

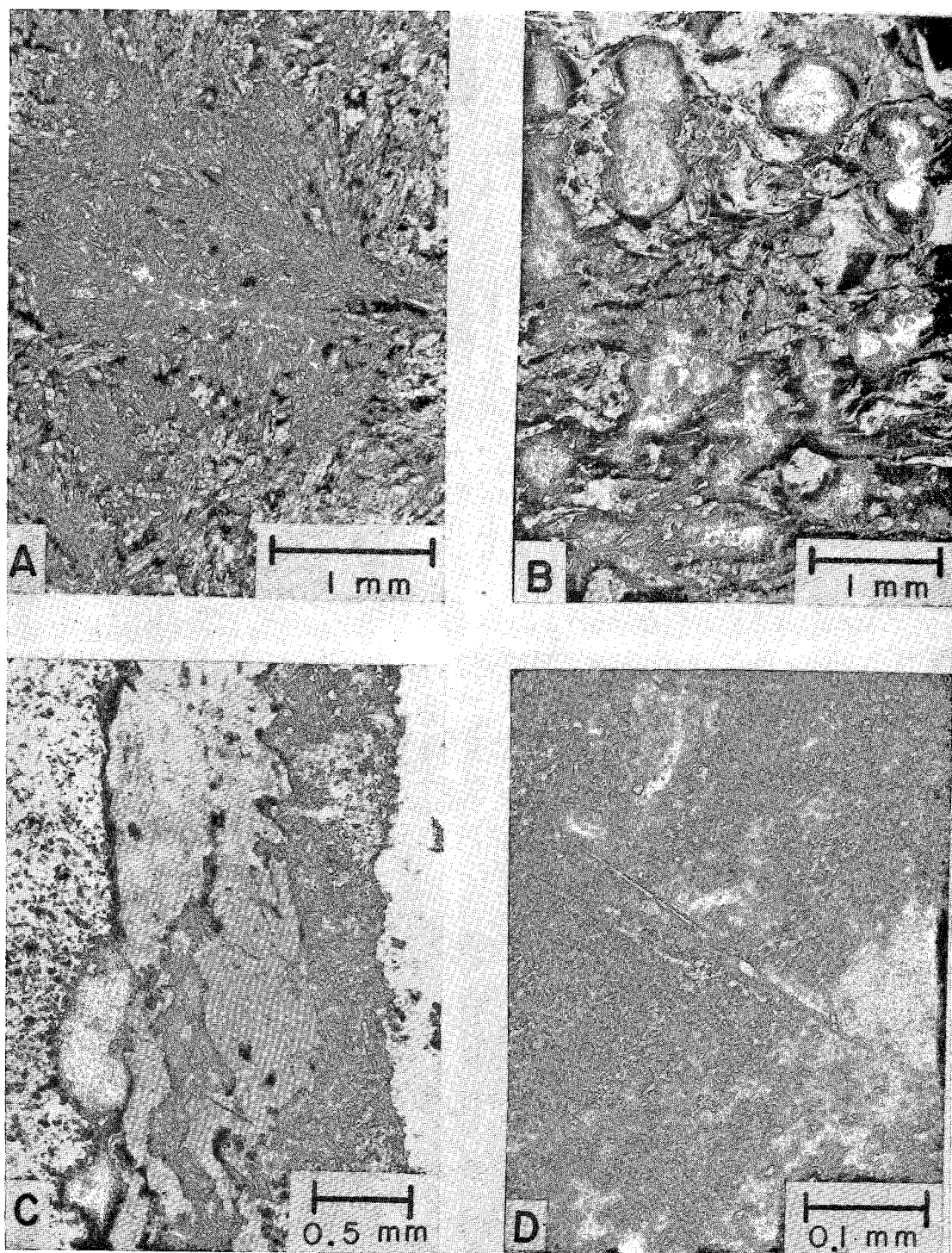
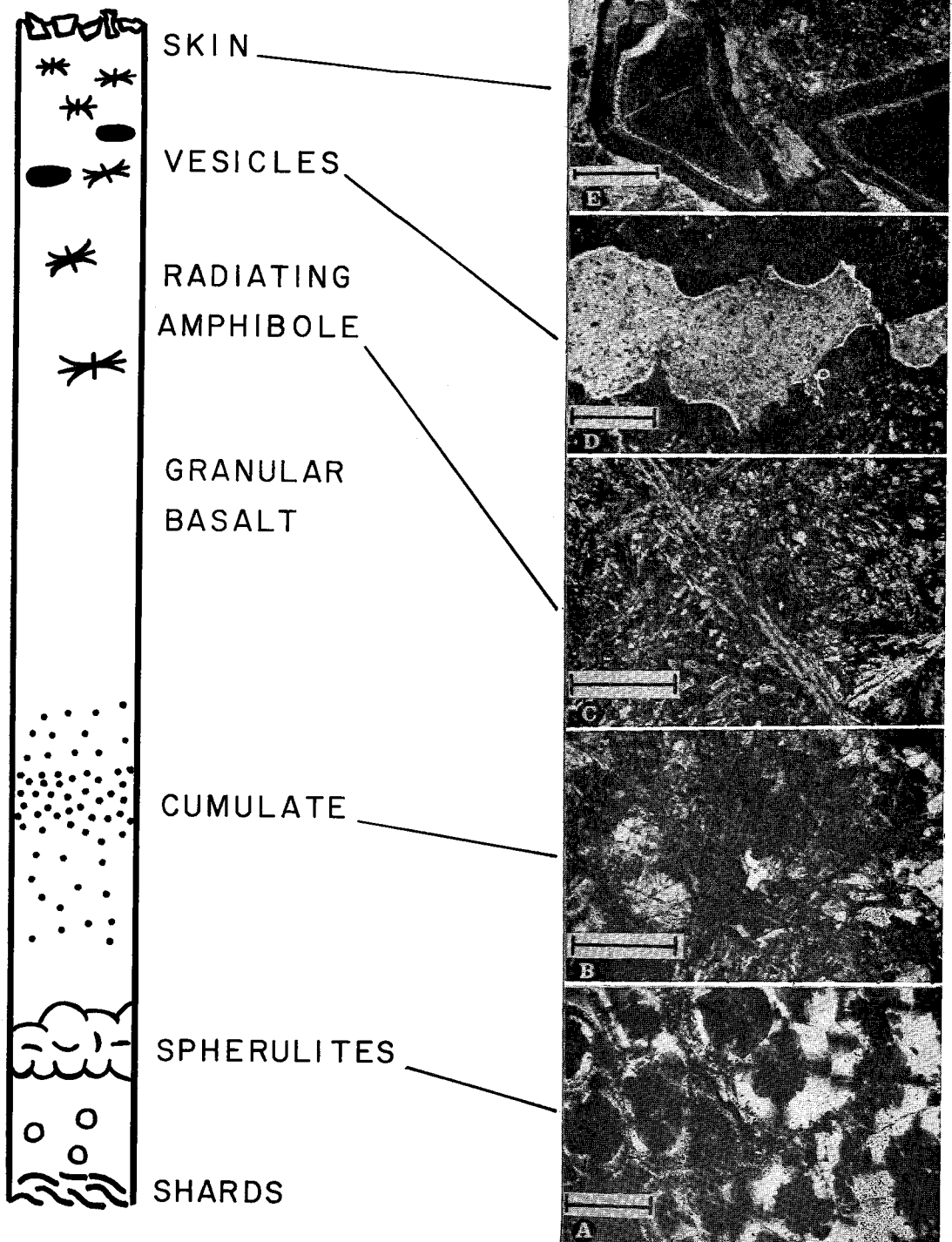


FIG. 2a: Radiating amphibole in a matrix of amphibole and plagioclase, Flow 1.

FIG. 2b: Contact between shards and spherulites at base of Flow 1.

FIG. 2c: Quartz-prehnite-actinolite-epidote-chlorite-magnetite-pumpellyite vein in chert below Flow 2.

FIG. 2d: Swallowtail quench plagioclase in the centre of a spherulite, Flow 1.



Columnar Section of Flow 1.

FIG. 3a: Spherulites with radially grown chlorite forming an interference mosaic matrix. Flow 1.

FIG. 3b: Microporphyrritic pyroxene and amphibole with a matrix of hornblende, plagioclase and quartz, Flow 1 cumulate zone.

FIG. 3c: Skeletal radiating amphibole, Flow 1.

FIG. 3d: Amygdule, formerly a segregation vesicle, Flow 1.

FIG. 3e: Concentrically zoned shards in flow-top skin, Flow 1.

Note: that the thickness of the zones in the column have been exaggerated. See text for the true thicknesses.

## MICROSCOPIC DESCRIPTION

The first of two flows selected for study is a 30- to 35-meter thick flow of high-iron basalt exposed near the main logging road. The base of the flow is a 1- to 2-cm thick layer of flattened structures which we interpret as former glass shards (Fig. 2b). They are now chloritized. Above this layer, there is a 10-cm zone of spherulites (Fig. 3a). These spherulites are radial intergrowths of plagioclase and a mafic mineral which have nucleated on skeletal quench plagioclase microlites (Fig. 2d). The spherulites now occur in a matrix of chlorite which has grown radially from the spherulites into a polygonal mosaic of mutually interfering domains, (Fig. 2b, 3a). Overlying the spherulitic zone is a 10-m microporphyritic layer (Fig. 3b) containing microphenocrysts of hornblende, some of which may be in part pseudomorphous after pyroxene, since they have pyroxene cores. Skeletal magnetite occurs locally.

The microporphyritic zone grades upward into a zone of granular hornblende basalt approximately 10 meters thick which, in turn, grades upward into a zone containing radiating hornblende (Fig. 2a), locally skeletal (Fig. 3c). We interpret this as a quench product\*. The quench texture appears at its lowest point in the flow as clusters of stubby, radiating hornblende crystals in an otherwise equigranular hornblende-plagioclase basalt, and reaches full development near the top of the flow as sets of frond-like growths of crystals several millimeters long, intergrown with plagioclase, and including some skeletal plagioclase microlites. No preferred orientation of the hornblende or plagioclase was observed.

Near the flow-top, composite amygdules similar to those described by Smith (1967) as segregation vesicles make up a few per cent of the rock (Fig. 3d). The segregation vesicles have sharply defined inner surfaces resulting from the re-entry of lava into the vesicles. Surrounding each vesicle is a darker zone with gradational outer boundaries. The segregation vesicles occur in a fine-grained radiating amphibole rock, and typically contain late fillings of quartz, chlorite, epidote, and sulphides, with occasional actinolite.

The flow is capped by a thin skin of ropy lava containing former glass fragments (Fig. 3e) which shows the effects of repeated fracturing as the flow moved. The shards of broken

glass contain skeletal plagioclase microphenocrysts. Like all of the finest-grained rocks in the study area, the flow top is veined with quartz on a fine scale, and is thoroughly chloritized.

The second flow selected for detailed study lies in the northeastern part of Thackeray Township. The lower 65 m of the flow are exposed and it is not high-iron basalt by our definition. The base of the flow is a fine-grained, chloritized, basalt. Above the base is a microporphyritic layer, containing mostly pyroxene, with some hornblende, and amphibole of deuteritic origin. Plagioclase phenocrysts up to 3 cm in size increase in amount upward in the flow, then end abruptly in a thick layer (Fig. 1d). Flow 2 contains no radiating amphibole in the exposed part.

## INTERPRETATION OF TEXTURAL VARIATIONS

We interpret the textural features of Flow 1 as follows. The shards at the base are the chloritized skin or rubble formed as the flow was moving, and were flattened by the weight of the overlying flow. The spherulitic layer immediately above the base is due to devitrification of the glassy bottom of the flow after the flow had stopped moving (since the spherulites are not deformed). The skeletal microlites of plagioclase are quench crystals formed during post-eruptive crystallization of the flow. The amphibole and pyroxene phenocrysts of the microporphyritic zone are cumulate minerals formed while the flow slowly cooled, and which have settled towards the base. There is some evidence of magmatic reaction between the pyroxene and amphibole, but we are not sure of its extent. The radiating amphibole fronds associated with quench plagioclase are quench crystals. We feel they cannot be metamorphic minerals because they show definite stratigraphic variations (in size and amount) within the flow, and they are not present in some of the nearby flows which have the same grain size and mineralogy, and have presumably undergone the same metamorphism. The alteration of the glassy parts of the flow may have begun during the eruptive phase by reaction with sea water, but this is difficult to prove.

Flow 2 is similar to Flow 1 except that it lacks quench amphibole, implying, we feel, a lower water content at eruption. It also has a layer of large plagioclase phenocrysts, which we interpret as due to crystal fractionation by flotation. The upper contact of the flow is not exposed, and the features at the base are not clear because the base is intimately associated with a 15-m thick underlying fragmental unit.

\*By quench product we mean crystals grown from the liquid during relatively rapid cooling of the flow. The growth rate is relatively rapid for the mineral species involved so that the typical form is skeletal or feathery.

TABLE 1. WHOLE ROCK ANALYSES FROM THACKERAY TOWNSHIP, SOME PUBLISHED ANALYSES FOR COMPARISON, AND ELECTRON PROBE ANALYSES OF AMPHIBOLES

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
S <sub>10</sub> 2	47.10	48.90	47.00	47.10	47.70	48.30	46.50	47.60	46.90	49.30	52.00	47.40	47.10	47.20	49.50
T <sub>10</sub> 2	0.93	0.87	0.83	0.78	0.75	0.73	0.73	0.69	0.73	0.74	0.74	0.80	0.66	0.70	0.71
Al <sub>2</sub> O <sub>3</sub>	14.45	14.70	14.38	14.00	14.43	14.75	14.03	15.30	15.40	16.50	15.10	14.30	14.60	13.90	7.40
Fe <sub>2</sub> O <sub>3</sub>	2.23	1.77	1.66	1.71	1.58	1.40	1.66	1.44	1.54	1.42	1.63	1.73	1.43	1.59	1.26
FeO	12.66	10.06	9.39	9.69	8.95	7.95	9.44	8.13	8.76	8.03	9.24	9.82	8.12	9.04	7.14
MnO	0.22	0.20	0.19	0.18	0.18	0.07	0.19	0.16	0.17	0.14	0.17	0.19	0.16	0.18	0.22
MgO	8.15	8.78	9.02	9.85	9.86	8.90	9.25	9.80	8.25	7.45	8.42	8.80	7.58	8.00	13.70
CaO	13.43	11.77	11.90	11.05	11.80	12.04	11.35	11.96	12.38	9.90	10.88	10.77	12.77	12.12	12.65
Na <sub>2</sub> O	2.00	0.98	1.63	1.30	1.37	1.20	0.75	1.23	1.40	1.70	1.82	0.09	2.10	1.00	1.72
K <sub>2</sub> O	0.23	0.47	0.32	0.34	0.28	0.32	0.21	0.29	0.37	0.39	1.02	0.93	0.59	0.45	1.70
P <sub>2</sub> O <sub>5</sub>	0.19	0.13	0.14	0.12	0.13	0.11	0.15	0.13	0.17	0.19	0.15	0.13	0.14	0.14	0.20
SUM	101.59	98.63	96.46	96.12	97.03	95.77	94.26	96.73	96.07	95.76	101.17	94.96	95.25	94.32	96.20
Height*	0	3.0	7.0	7.4	11.1	17.8	21.1	23.3	28.5	32.2	34.4	40.7	41.5	48.5	49.8
	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
S <sub>10</sub> 2	51.10	49.80	48.20	50.50	51.20	50.30	50.00	50.05	49.00	51.90	49.34	50.22	48.50	51.16	49.91
T <sub>10</sub> 2	1.42	1.72	2.65	1.75	1.81	1.82	1.70	1.58	1.97	1.67	1.49	2.03	0.48	0.36	0.43
Al <sub>2</sub> O <sub>3</sub>	13.60	12.90	10.50	12.50	12.95	12.30	12.60	13.20	12.05	12.70	19.04	13.62	9.60	3.81	5.30
Fe <sub>2</sub> O <sub>3</sub>	2.04	2.14	2.82	2.12	2.31	2.15	2.23	2.05	2.14	2.04	1.99	2.21	2.25	-	-
FeO	11.56	12.15	15.98	12.03	13.09	12.20	12.66	11.64	12.11	11.56	6.82	12.36	17.18	22.51	18.47
MnO	0.19	0.22	0.25	0.19	0.20	0.20	0.20	0.19	0.25	0.22	0.17	0.26	0.57	0.61	0.41
MgO	7.00	6.80	6.15	5.95	6.70	6.60	6.95	6.72	5.97	5.87	7.19	4.36	8.63	8.64	11.09
CaO	9.34	9.40	6.32	8.40	8.82	8.75	9.55	8.75	9.90	8.98	11.72	8.47	10.20	11.52	11.68
Na <sub>2</sub> O	2.02	1.80	1.90	2.10	2.10	1.45	1.68	2.48	2.80	2.95	2.73	3.26	0.66	0.61	0.71
K <sub>2</sub> O	0.68	0.61	0.11	0.65	0.55	0.55	0.36	0.57	0.42	0.37	0.16	0.36	0.08	0.11	0.11
P <sub>2</sub> O <sub>5</sub>	0.22	0.25	0.38	0.28	0.28	0.27	0.20	0.25	0.31	0.24	0.16	0.36	0.00	-	-
SUM	99.17	97.79	95.26	96.47	100.01	96.59	98.13	97.48	96.92	98.50	98.81	97.51	98.15	99.33	99.01
Height*	3.3	1.5	14.8	20.4	25.8	29.3	1.1	11.9	34.8	27.8					

FLOW 2 - rocks from the T-73 series: analysis (1) T-73-93, (2) 96, (3) 97, (4) 98, (5) 99, (6) 100, (7) 101, (8) 102, (9) 104, (10) 105, (11) 107, (12) 109, (13) 110, (14) 111, (15) 112.

FLOW 1 - rocks from the T-73 series: (16) T-73-12, (17) 28, (18) 31, (19) 32, (20) 33, (21) 34, (22) 35, (23) 38, (24) 42, (25) 51.

(26) Average oceanic tholeiitic basalt (from Engel *et al.* 1965). (27) Diabase cutting volcanic rock (Fratta & Shaw 1974).  
 (28) Amphibole used in modelling fractionation of Flow 1. (29) Actinolite in vein with prehnite.  
 (30) Quench amphibole from a high-iron basalt.

\*Height in meters, above the flow base.

### CHEMISTRY

Analyses of the two Thackeray basalt flows are presented in Table 1. All analyses were produced by XRF techniques except MnO which was done by atomic absorption. Because of

variable oxidation in the coarser parts of flows, all analyses have had their iron content adjusted to make Fe<sub>2</sub>O<sub>3</sub> = 15% of total iron as FeO in weight units. This is the Fe<sup>2+</sup>/Fe<sup>3+</sup> ratio for the quench amphibole rocks which are thought to be the least altered.

Flow 1 is a high-iron basalt similar to other basalts in Thackeray Township (other analyses will be presented at a later date), and similar to the high-iron basalts of Garrison Township to the north (Goodwin 1972). These rocks probably represent a single high-iron basalt series (Fig. 4). These basalts are broadly similar to the ocean tholeiite of Engel *et al.* (1965), see Table 1 #26, but they have substantially more iron and less Al<sub>2</sub>O<sub>3</sub> and CaO. This rock type closely resembles the diabase dykes which form major swarms in the Canadian Shield (Fratta & Shaw 1974), see Table 1 #27. We have found similar high-iron basalts in other greenstone belts in the Superior Province, for example, Pickle Crow. It may be, therefore, that this magma type was a fairly common product of Archean volcanism and possibly characteristic of certain stages in the growth of the volcanic edifices. More work remains to be done on this subject. Flow 2 is not a high-iron basalt by our definition; it more closely resembles a typical tholeiite.

At the present time we do not have a good explanation for the high iron content of these

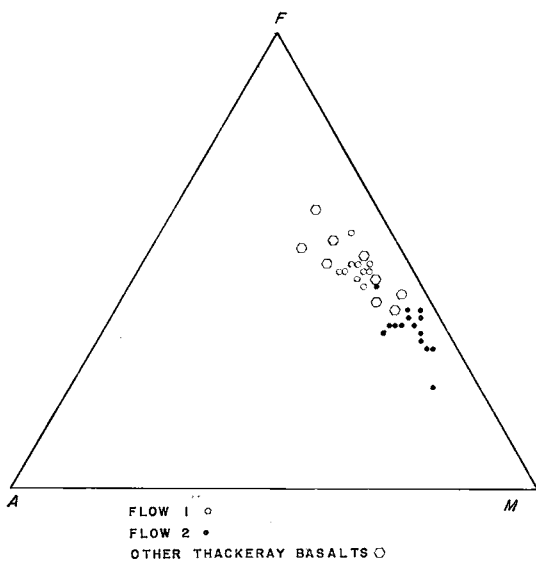


FIG. 4: AFM diagram for meta-basalts from Thackeray Township.

Archean magmas. Modelling work which will be presented at a later date appears to indicate that this is probably a feature of the original primitive magma rather than a result of differentiation.

DIFFERENTIATION

A fractionation model has been developed based on our interpretation of the textures and tested using the chemistry of the flows. For Flow 1 we postulate a homogeneous magma erupted as a thick flow on the ocean floor. The liquidus phase under the conditions of eruption was plagioclase which grew as microlites on quenching of the margins of the flow. As the flow cooled further, conditions of temperature, pressure, and composition (especially water content) were such that amphibole formed as quench crystals; these are fine near the flow top, but become coarser due to slower growth lower in the flow. Within the still liquid part of the flow, more equant amphibole, and some pyroxene, formed and settled to the bottom, giving a depleted zone near the centre of the flow, and a cumulate layer near the base (the microporphyrific zone). We are not certain at this point of our modelling what proportion of pyroxene was originally present in the cumulate, but it may have been relatively small. At some stage Fe/Ti oxide formed, and may have settled to some extent.

We have tested this model using the available chemical data, and the method of graphical analysis using molecular ratio diagrams developed by Pearce (1968). Interested readers should review this work in order to understand our reasoning in detail.

Briefly, in a series of rocks related by crystal fractionation, if the molar amounts of two chemical species in a series of chemical analyses are divided by the molar amount of a species not involved in the fractionation (a constant species), and the resulting points are plotted on a diagram, the diagram is a molecular ratio diagram. The slope of the trend for any pair of species is the molar ratio of those species in the fractionated mineral or mineral mixture.

Because there is no evidence for the crystallization of any phosphorus-bearing mineral before the crystallization of the Thackeray flows was well-advanced, we postulate that phosphorus was a constant element during the fractionation of the Thackeray flows, and can be used to normalize the molecular ratio diagrams for the flows.

Our analysis of the data and our fractionation model, assuming dominant amphibole fractiona-

tion, is shown in Figure 5. The amphibole which we have used is a cumulate amphibole analysed by electron microprobe (Table 1, no. 28). Point P in Figure 5 is the assumed parent composition of the flow — a well-preserved quench amphibole rock (#20 in Table 1). Point D is the model differentiate, the parent with 30% by weight of hornblende removed. Point C is the model cumulate rock, the parent with 30% of hornblende added. Addition of about 40% hornblende to the parent adequately accomplishes the most extreme chemical differentiation observed (#22 in Table 1). Deviations from simple linear relationships on the molecular ratio diagrams are probably the result of minor pyroxene fractionation, and minor movement of plagioclase crystals enclosed in cumulate amphibole or pyroxene. Because of the generally good fit of the model to the data we feel that variations and errors in P<sub>2</sub>O<sub>5</sub> have not significantly affected the results.

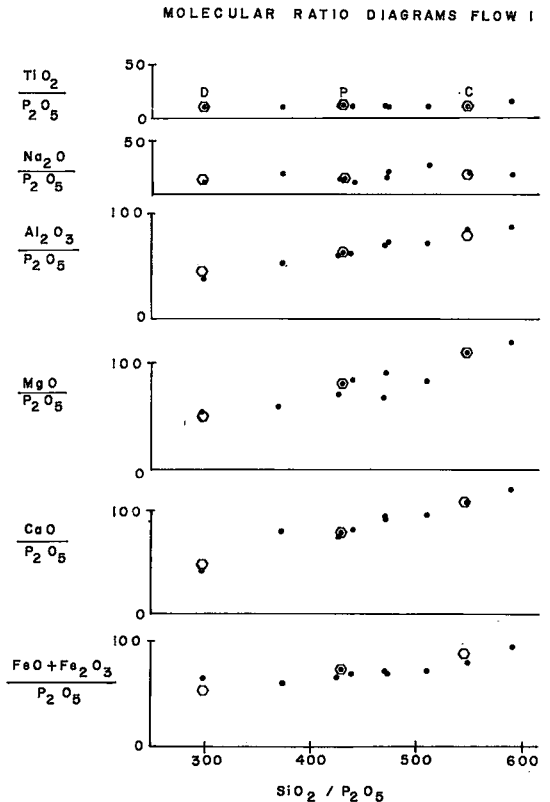


FIG. 5: Molecular ratio diagrams for Flow 1. Point "P" is the model parent composition, "C" is the model cumulate composition, and "D" is the model differentiate composition. Points lying to the right of "P" are cumulate rocks, those to the left are depleted rocks in the flows.

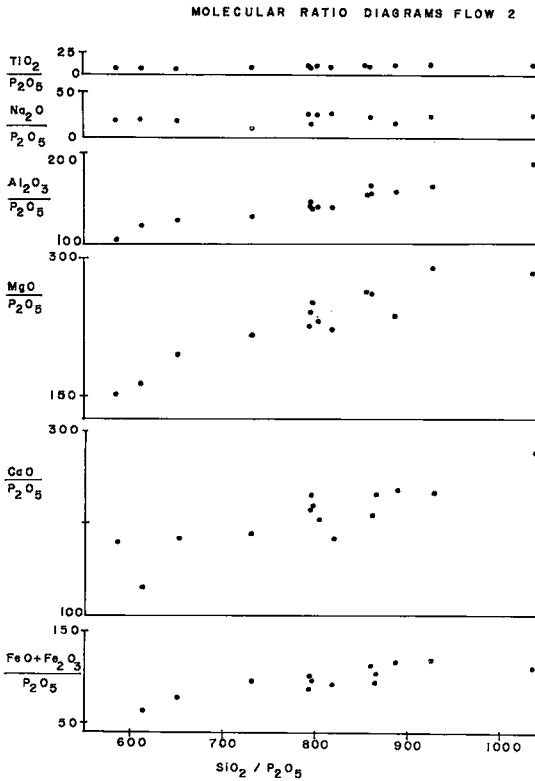


FIG. 6: Molecular ratio diagrams for Thackeray Flow 2.

The molecular ratio diagrams for Flow 2 (Fig. 6) show more scatter than those for Flow 1. This difference is believed to be the result of fractionation, and uneven accumulation, of pyroxene, amphibole, and plagioclase. Because fractionation of these three phases would have different intersecting trends on several molecular ratio diagrams, and the relative contribution of each phase has not been evaluated, no quantitative model has been formulated at this time for Flow 2.

Cursory examination of the major and minor element in the analyses of Flow 1 in Table 1 shows that, for the most part, the major constituents such as  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{MgO}$ , and  $\text{CaO}$  do not appear to vary (in weight %) as much as some of the minor elements such as  $\text{K}_2\text{O}$  and  $\text{P}_2\text{O}_5$ . At first, it might seem paradoxical that differentiation can apparently affect major elements less than minor or trace elements. This is a necessary consequence of crystal fractionation involving a phase whose major element chemistry closely resembles that of the parent liquid (for example, clinopyroxene or amphibole fractionating from basalt). The elements which

are not involved in the fractionation process (mainly the so-called incompatible elements) are "increased" or "decreased", while the major elements involved in the fractionation show "less" change in simple weight comparisons. The net result is that weight per cent comparisons do not show the fractionation process in an easily understood manner. Molecular ratio diagrams as used here, on the other hand, illustrate the process in a more readily comprehensible manner. This flaw in traditional methods of analysis (such as Harker diagrams) has been documented for the Palisade Sill (Pearce 1970).

### METAMORPHISM

Generalizing from the study of Flows 1 and 2, metamorphism in Thackeray Township can be described as having taken place in three stages (excluding late quartz-vein formation). The earliest stage was the initial deuteric alteration of the flows, the second stage was prehnite-pumpellyite facies metamorphism, and the third stage was later, low-pressure metamorphism related to the emplacement of the Garrison Syenite. We emphasize again that the metamorphism of these rocks is incomplete and that most of the original igneous mineral species have been locally preserved.

During the initial deuteric alteration the finer-grained parts of the flows were partly hydrated, and probably reacted with sea water. Features which we infer to have formed at this stage and that survived to the present include zoning in originally glassy volcanic fragments, quartz veining on a fine scale in flow margins, and albization along fractures, usually in brecciated units (Fig. 1c). Some chlorite probably grew directly from the glass at this stage (Fig. 2b).

The second stage of metamorphism was marked by continued burial, with  $P$ - $T$  conditions reaching those of the prehnite-pumpellyite-quartz facies. In this stage the central parts of the flows were partly hydrated. Plagioclase phenocrysts were partly replaced by prehnite, clinozoisite, calcite, quartz, and possibly calcium montmorillonite. Pumpellyite formed in pyroxene crystals. Vesicles contain assemblages of prehnite, quartz, chlorite, calcite, and albite with epidote, or pyrite. All assemblages existed in close contact with magnetite and sphene. Muscovite is present in small amounts in the rocks, and may have been a stable mineral at this stage.

During burial metamorphism, monomineralic aggregates of calcite, clinozoisite, or albite developed, generally on a microscopic scale, indicating that sodium and calcium (and possibly



other elements) were able to migrate in the rock over a distance greater than several millimetres. Quartz-calcite-chlorite veins probably also formed during this second stage of metamorphism.

During the third stage of metamorphism, prehnite was restricted to calcium-rich environments (former plagioclase phenocrysts), leaving in its place in the groundmass distinctive aggregates of quartz grains (Jolly, personal communication, 1974). The prehnite co-exists with clinozoisite, quartz, albite, chlorite, muscovite, and probably calcium montmorillonite. Pumpellyite remained the stable phase replacing pyroxene phenocrysts, while in the groundmass the stable metamorphic assemblage is some or all of quartz, epidote, actinolite, chlorite, albite, calcite, muscovite. All phases exist in close proximity with sphene and magnetite.

Worthy of special consideration are two seven-mineral assemblages.

1. quartz-chlorite-epidote-actinolite-pumpellyite-magnetite-calcite inferred from observations of Flow 2.
2. quartz-prehnite-pumpellyite-epidote-actinolite-chlorite-magnetite, observed in a single thin section from a vein in chert about 100 m stratigraphically below Flow 2 (see Fig. 2c).

If we assume that the compositions of all the minerals are adequately represented in the model system  $\text{SiO}_2 - \text{Al}_2\text{O}_3 - \text{Fe}_2\text{O}_3 - (\text{Fe}, \text{Mg})\text{O} - \text{CaO} - \text{CO}_2 - \text{H}_2\text{O}$ , then both assemblages would be isothermally univariant in  $\mu_{\text{CO}_2} - \mu_{\text{H}_2\text{O}} - P_{\text{solids}}$  space. On any two-dimensional isothermal section of this space (such as the isobaric  $\mu_{\text{CO}_2} - \mu_{\text{H}_2\text{O}}$  diagram) all seven minerals of each assemblage could co-exist stably only at an invariant point. Using the mineral formulae in Table 2, the "reactions" among these mineral assemblages have been deduced and balanced. The equilibrium curves of the 7-phase assemblages are shown in Figures 7 and 8. The slope of an equilibrium curve on a  $P_s - \mu_{\text{H}_2\text{O}}$  diagram is given by

$$\frac{dP_s}{d\mu_{\text{H}_2\text{O}}} = \frac{dn_{\text{H}_2\text{O}}}{dV_s} \quad (41.84)$$

TABLE 2. STRUCTURAL FORMULAE AND MOLAR VOLUMES OF MINERALS USED TO CALCULATE THE INVARIANT POINTS OF FIGURES 7 AND 8

	Pr	P	Q	C	Cl	E	Ac	M
$\text{SiO}_2$	3.00	6.00	1.00	0.00	5.46	3.00	8.00	0.00
$\frac{1}{3}\text{Al}_2\text{O}_3$	1.90	4.00	0.00	0.00	5.04	2.25	0.00	0.00
$\frac{1}{2}\text{Fe}_2\text{O}_3$	0.10	1.00	0.00	0.00	0.05	0.75	0.00	1.00
$(\text{Fe}, \text{Mg})\text{O}$	0.00	1.00	0.00	1.00	9.46	0.00	5.00	1.00
CaO	2.00	4.00	0.00	1.00	0.00	2.00	2.00	0.00
$\text{H}_2\text{O}$	1.00	3.50	0.00	0.00	8.00	0.50	1.00	0.00
$\text{CO}_2$	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00
$V(\text{cc/mole})$	141.10	298.00	22.69	36.90	426.30	139.00	280.00	44.52

Pr prehnite P pumpellyite Q quartz C calcite Cl chlorite  
E epidote Ac actinolite M magnetite

where  $n_{\text{H}_2\text{O}}$  is the number of moles of water involved in the reaction, and  $dV_s$  is the change in volume of the solid phases in the reactant and product assemblages.

Figure 7a illustrates that increasing the chemical potential of  $\text{CO}_2$  relative to that of  $\text{H}_2\text{O}$  suppresses the stability fields of pumpellyite and epidote-actinolite assemblages in favour of calcite-chlorite assemblages. Figure 7b, shows that decreasing  $P_s$  (at constant  $T, \mu_{\text{H}_2\text{O}}, \mu_{\text{CO}_2}$ ) would have the same effect.

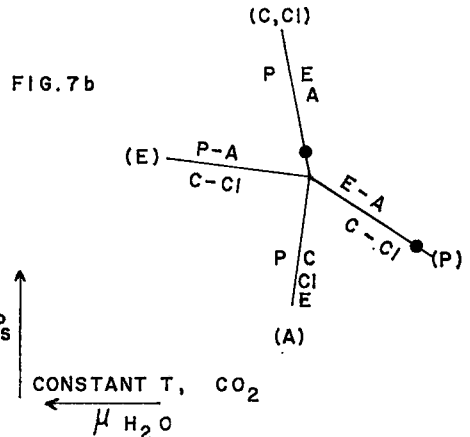
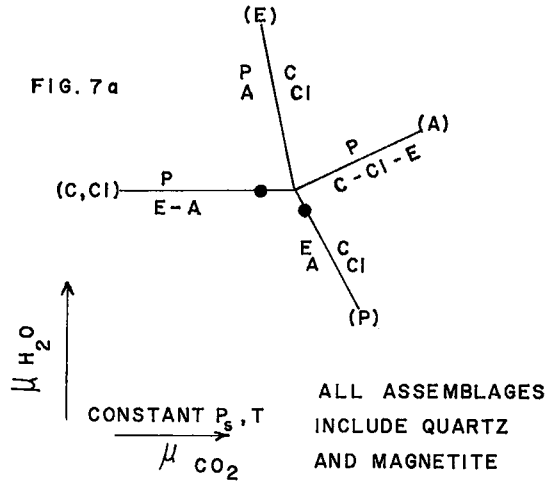


Fig. 7a: The invariant point quartz-magnetite-epidote-actinolite - calcite-chlorite-pumpellyite at constant  $P_s$  and  $T$ .

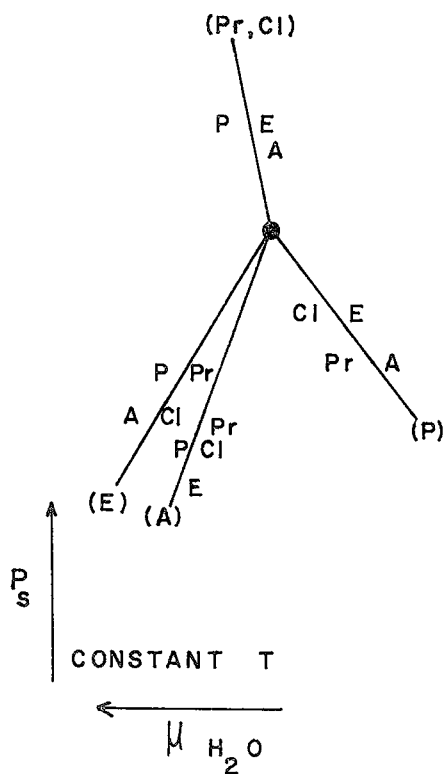
Fig. 7b: The invariant point of Figure 7a at constant  $T, \mu_{\text{CO}_2}$ . The two diagrams represent orthogonal planes in  $P_s - \mu_{\text{H}_2\text{O}} - \mu_{\text{CO}_2}$  space at constant  $T$ .

Solid circles indicate observed assemblages of metamorphic minerals.

Q-quartz, M-magnetite, E-epidote, A-actinolite C-calcite, Cl-chlorite, P-pumpellyite.

Figure 8 shows that the prehnite-pumpellyite stability field is relatively unaffected by changing  $P$  (at constant  $T$ ,  $\mu_{\text{H}_2\text{O}}$ ,  $\mu_{\text{CO}_2}$ ) but that the assemblage chlorite-prehnite has an upper limit of  $P$  that is independent of  $\mu_{\text{CO}_2}$ .

The assemblages associated with the late thermal event are similar to those reported by Coombs *et al.* (1970) for the Northern Appalachians. Since the stratigraphic interpretation of the Abitibi Greenstone Belt implies prehnite-pumpellyite facies metamorphism at considerable depth because of the great thickness of volcanic rocks, we infer that there must have been a break in time between stages 2 and 3, although the maximum temperatures during these stages may have been quite similar.



#### ALL ASSEMBLAGES INCLUDE QUARTZ AND MAGNETITE

Fig. 8 The invariant point quartz-magnetite-epidote-actinolite-pumpellyite-prehnite-chlorite at constant  $T$ , below a threshold value of  $\mu_{\text{CO}_2}$  which would add calcite to the observed assemblage. Solid circle indicates the observed assemblage. Q-quartz, M-magnetite, E-epidote, A-actinolite, P-pumpellyite, Pr-prehnite. Cl-chlorite

Since prehnite is still present in the Thackeray rocks, and assuming equilibrium, conditions of the last thermal metamorphic event could not have exceeded  $400^\circ\text{C}$ , the upper thermal stability limit of prehnite (Liou 1971). We feel that the pressure on the rocks at the time of the last thermal event may have been quite low, perhaps as low as 2 kb.

Samples selected for chemical analysis were generally massive rocks, although samples with small amounts of veins or amygdules were also analyzed. Despite wide variations in grain size, and degree of hydration, the rocks within each flow show coherent trends on molecular ratio diagrams (Fig. 5, 6). The position of the rocks in the molecular ratio diagram is consistent with the position inferred from our interpretation of the rock texture. We believe that this indicates that, except for the addition of water, and some carbon dioxide, the massive rocks of the flows have suffered little change in their bulk composition. We do not extend this interpretation to zoned volcanic fragments or to rocks with large amounts of quartz or quartz-chlorite veining.

#### CONCLUSIONS

The two Archean submarine metabasalt flows from Thackeray Township which have been reported in this work, have been metamorphosed to prehnite-pumpellyite quartz facies conditions. Their well-preserved textures and primary minerals suggest that, apart from  $\text{CO}_2$  and  $\text{H}_2\text{O}$ , the central parts of the flows have retained their original composition. The basalts have a high-iron content and we suggest that this is a magma type which is probably widespread in the Archean. The flows are about 35 meters thick, and have differentiated during post-eruptive crystallization. The flows crystallized skeletal plagioclase (the inferred liquidus phase), hornblende, and Fe-Ti oxide. The presence of skeletal and frond-like hornblende in the upper part of an iron-rich basalt flow suggests that the hornblende may have grown as a quench phase, and was probably metastable. The differentiation of the flows can be modelled by crystal fractionation in which hornblende plays a key role. In the iron-rich flow, crystal settling of hornblende (40% by weight added to the parent composition) produces the most extreme cumulate composition. We feel that the iron-rich nature of these basalts, which are similar to the ones in Garrison Township to the north, probably reflects the original composition rather than fractionation of a more "primitive" magma type.

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